How a Nuclear Reactor Works Notes

Nuclear reactor science is a complicated subject. It's all about neutrons – how they are generated and how the reactor neutron population is controlled through proper reactor design and operation. This presentation will introduce reactor kinetics concepts with sufficient detail to facilitate a basic understanding of how nuclear reactors work.

Slide 6 – coal-fired power plant graphic

- graphic illustrates how heat generation controlled in fossil-fueled power plant
- coal or natural gas fed to boiler, where ignited by flame
- amount of heat generated controlled by rate at which fuel fed to boiler
- heat generation terminated by stopping supply of fuel to boiler

Slide 7 – pressurized water reactor power plant graphic

- graphic illustrates how heat generated in nuclear power plant
- since nuclear reactor contains sufficient nuclear fuel for 1 to 2 years of continuous operation, heat generation rate is controlled by limiting
  - how much fuel exposed to neutrons that can cause U-235 fission, and
  - thermal neutron population available to cause U-235 fission
- in both PWR and BWR, neutron-absorbing control rods used to limit fuel exposure to fission neutrons
- thermal neutron population available to cause fission is controlled by
  - using boric acid dissolved in PWR coolant water (boron absorbs neutrons)
  - regulating reactor coolant water flow through BWR core (controls neutron moderation to thermal energies)
- heat generated by fission terminated by fully inserting control rods into reactor core

Slide 8 – power plant operation comparison

- key to proper operation of power plant – heat removal rate from boiler in fossil-fueled plant, or reactor core in nuclear plant, must be matched to heat generation rate
- if heat generation rate exceeds heat removal rate, potentially damaging plant condition can be created, depending on magnitude of excursion and duration
- while shutting down fossil-fueled power plant terminates all heat generation, nuclear power plant continues to generate heat following shutdown from radioactive decay of fission products in nuclear fuel

- decay heat must be removed for weeks following reactor shutdown to keep fuel from overheating and ultimately melting
  - integrity of fuel pellet and fuel rod barriers to radioactive material release must be preserved by continuing to remove radioactive decay heat
  - at one month following reactor shutdown, decay heat power still about 0.1% of reactor operating power prior to shutdown

Slide 12 – PWR pressure vessel graphic
- graphic shows PWR pressure vessel
- reactor pressure vessel contains nuclear fuel assemblies and moveable neutron-absorbing control rods;
  - control rod guide tubes penetrate top of pressure vessel
  - control rod drive mechanisms located on top of pressure vessel

Slide 13 – BWR pressure vessel graphic
- graphic shows BWR pressure vessel
- steam separators and steam dryers located in top of pressure vessel
- control rods enter reactor core from bottom of pressure vessel

Slide 14 – reactor core barrel graphic
- nuclear fuel assemblies contained within reactor core barrel that fits inside reactor pressure vessel

Slide 15 – PWR fuel assembly graphic
- graphic illustrates PWR fuel assembly where neutron absorbing control rods located within fuel assembly
- nuclear fuel assemblies consist of array of fuel rods through which cooling water flows to remove heat produced by fission in nuclear fuel

Slide 17 – initial source of reactor neutrons
- startup neutron sources used for stable and reliable initiation of fission chain reactions in nuclear reactors
- startup sources removed from reactor core, usually after few months, as neutron capture resulting from thermal neutron flux in operating reactor core changes composition of isotopes, and thus reduces useful lifetime as neutron sources

Slide 19 – example neutron source locations in PWR fuel assemblies
- reactor core map shows typical configuration of startup sources in PWR fuel assemblies (red circles)
- sources positioned so neutron flux they produce always detectable by ex-core reactor monitoring instruments

Slide 20 – example neutron source locations in BWR fuel assemblies

- reactor core map shows typical configuration of startup sources between BWR fuel assemblies

Slide 22 – neutron interactions with U-235 graphic

- fission is only one of possible interactions of neutron with U-235 atom
- neutron may also be involved in scattering interactions and non-fission capture interactions with U-235 atom
  - inelastic collision produces gamma-ray
  - transmutation (neutron capture event) produces free proton or alpha particle
  - radiative capture event produces gamma-ray
  - fission event produces fission fragments and free neutrons
- each of possible interactions has associated probability dependent on neutron energy

Slide 24 – cross-sectional area vs incident neutron energy illustration

- graphic is visual aid to understanding relationship between interactive cross-section and incident neutron energy; that is, relative interaction probability
- interaction cross-section relatively small for high energy neutron and relatively large for low energy neutron

Slide 26 – U-235 fission cross-section vs neutron energy graphic

- graphic shows how U-235 fission cross-section varies with neutron energy; note log scales on both axes
- 1 MeV is average energy of neutrons born from U-235 fission
  - referred to as fast neutrons
  - U-235 fission cross-section defined as 1 barn for 1 MeV neutrons
- 0.025 eV is average energy of neutrons in thermal equilibrium with their surroundings
  - referred to as thermal (or slow) neutrons
- neutron cross-sections for energies between 1 and 100 eV show resonance peaks associated with energies that closely match discrete quantum energy levels of nucleus; all fissionable materials exhibit similar resonance behavior

Slide 28 – neutron multiplication factor graphic

- graphic helps to visualize relationship between neutron multiplication factor and neutron population
- subcritical reactor ($k < 1$) does not generate sufficient neutrons to achieve self-sustaining chain reaction
- supercritical condition ($k > 1$) results in increasing neutron population and therefore more fission events
  - if k large enough, could lead to uncontrollable fission chain reaction

Slide 32 – neutron life-cycle graphic

- graphic illustrates nuclear reactor neutron life cycle, showing various neutron production and loss events
- illustration begins with 1000 fission neutrons from U-235 fission and ends with 1000 neutrons; that is, next neutron generation also begins with 1000 neutrons, so neutron population is stable and k = 1
- neutron life-cycle events include
  — production of neutrons from fast fission of U-235
  — loss of fast neutrons due to leakage from reactor core
  — loss of neutrons due to non-fission capture by U-238 in resonance energy region
  — loss of thermal neutrons due to leakage from reactor core
  — loss of thermal neutrons due to absorption in non-fuel materials
  — production of neutrons from thermal fission of U-235
- to incrementally increase reactor power level, neutron population must be increased by small amount in each successive generation
  — either neutron production must be increased or neutron losses decreased so k greater than 1
- likewise, to decrease reactor power level, neutron population must be decreased in each successive generation
  — either neutron production must be decreased or neutron losses increased so k less than 1

Slide 35 – U-235 fission cross-section vs neutron energy graphic
- small probability that neutrons of 1 MeV energy will produce fission of U-235 atoms

Slide 37 – fast neutron leakage illustration
- some fast (high energy) neutrons escape from periphery of reactor core

Slide 39 – U-238 resonance capture illustration
- as with U-235 fission cross-section, the U-238 neutron absorption cross-section increases as neutron energy decreases
- in resonance range of neutron energies, U-238 atoms compete probabilistically with U-235 atoms for capturing neutrons
- decreases neutron population achieving thermal energy since so many more U-238 atoms than U-235 atoms in nuclear reactor fuel

Slide 41 – thermal neutron leakage illustration
- some thermal (low energy) neutrons escape from periphery of reactor core

Slide 43 – thermal neutron absorption illustration

- while most neutron absorption occurs in control rods used to control reactor power, some neutrons absorbed by reactor structural materials

Slide 44 – cross-sections of reactor materials

- note large thermal neutron capture cross-sections for boron-10, cadmium, xenon-135, and samarium-149
  - most Xe-135 in reactor fuel results from radioactive decay of fission product tellurium-135
  - Xe-135 removed from reactor fuel by radioactive decay or by neutron capture to produce stable Xe-136
  - during reactor operation, Xe-135 builds up to equilibrium level where rate of production from Te-135 equal to rate of removal by radioactive decay and neutron capture
  - stable Sm-149 produced in reactor fuel from radioactive decay of fission product neodymium-149
  - Sm-149 removed from reactor fuel by neutron capture to produce stable Sm-150, which has very much smaller neutron capture cross-section
  - like Xe-135, Sm-149 builds up in nuclear reactor fuel to equilibrium level during reactor operation

Slide 46 – U-235 cross-sections for capture and fission interactions

- slide shows that some thermal neutrons captured by U-235 don't result in fission
- ratio of neutron capture cross-section to total neutron absorption cross-section for thermal neutrons approximately 14.4% (approximately 14.4% of thermal neutrons captured by U-235 nucleus will not result in fission event)
- non-fission events will produce U-236 (23-million-year half-life), which decays by alpha particle emission to thorium-232

Slide 47 – neutron life-cycle time

- rate of change in reactor power determined by rate of change of fissions in reactor fuel, which is determined by mean neutron generation time
- *mean neutron generation time* of 10^{-4} second means that neutron population changes occur really fast – like by factor of 10,000 in one second
- such rapid changes beyond capability of reactor operator or automatic mechanical system actuation to control

Slide 51 – delayed neutrons (cont.)

- delayed neutrons emitted following beta decays of certain fission fragments known as *delayed-neutron precursors*; appear on time scale characteristic of precursor beta decay
- some delayed-neutron precursor beta decays leave daughter nucleus with enough excitation energy to expel a neutron

- about 20 different fission fragment nuclides identified as delayed-neutron precursors, including bromine-87, 88, and 89, arsenic-85, rubidium-93 and 94, iodine-137, 138, 139, and 140, tellurium-135 and 136, antimony-135, and tin-134
- *delayed neutron generation time* is long compared to *mean neutron generation time* of approximately 10^{-4} second

Slide 52 – delayed neutron illustration

- graphic shows various energies associated with beta particle emitted when bromine-87 fission fragment decays to krypton-87
- 2.5% of time, beta decay results in excited energy state of Kr-87 nucleus with sufficient energy to expel a neutron, thereby becoming stable Kr-86
- 97.5% of time, beta decay results in excited energy state of Kr-87 nucleus, which then emits gamma-ray to get to Kr-87 ground energy state
- Br-87 has longest half-life (about 56 seconds) of all delayed-neutron precursors

Slide 53 – delayed neutron fraction

- nuclear reactors designed to "go critical" with aid of delayed neutrons so that fission rate at criticality (i.e., change in reactor power) can be easily controlled
- effect of *delayed neutron generation time* (about 12.5 seconds) is to increase *neutron life-cycle time* from prompt neutron value of 10^{-4} second to 0.081 second – an effective 810-fold increase in neutron life-cycle time

Slide 57 – reactor criticality achieved with delayed neutrons

- positive reactivity change equal to delayed neutron fraction of 0.65% (prompt critical condition) would cause reactor power to increase by factor of approximately 3×10^5 in one second – highly uncontrollable condition
- typical positive reactivity changes in nuclear reactors much less than 0.1%
  - for positive 0.1% reactivity change reactor power would increase by factor of approximately 1.01 in one second (or factor of approximately 3.5 in 100 seconds)
  - this rate of increase in reactor power slow enough to allow for operator and automatic control system intervention to limit or terminate increase in power
- slight reactivity changes occur continuously in operating nuclear reactor due to variations in system physical parameters (e.g., fuel temperature, moderator temperature, moderator density, etc.)

Slide 58 – role of delayed and prompt neutrons in critical reactor conditions graphic

- graphic provides visual illustration of how delayed neutrons affect reactor control
- to achieve stable self-sustaining fission reaction (delayed critical), no excess reactivity (positive or negative) in reactor core
  - both prompt and delayed neutrons required to achieve and maintain delayed critical condition (k = 1)
- to increase reactor power level, positive reactivity less than delayed neutron fraction must be introduced into reactor core to create delayed supercritical condition
  - can be achieved by partially removing control rods from PWR reactor core or by increasing reactor coolant flow through BWR reactor core
  - some negative reactivity may be introduced into reactor core to re-establish delayed critical condition ($\rho = 0$) at new reactor power level (e.g., reinserting PWR control rods or decreasing BWR reactor coolant flow)

Slide 62 – power increase vs time as function of reactor period graphic

- graphic shows how (normalized) reactor power increases with time as function of reactor period
- as illustrated in graphic, short reactor periods of 10- and 20-seconds result in very rapid power increases
- typical positive reactivity changes in nuclear reactors significantly less than 0.1% to assure reactor period greater than 100 seconds
  - assures that any increase in reactor power slow enough to be easily within control capabilities of reactor operators

Slide 64 – estimated reactor period for positive reactivity changes graphic

- graphic illustrates estimated reactor period as function of reactivity inserted into reactor core
- for reference purposes, reactivity insertion equal to delayed neutron fraction, resulting in prompt critical condition, is 0.0065
- limiting reactor positive reactivity changes to much less than 0.1% provides reactor period much greater than 80 seconds to assure adequate control of reactor power increases

Slide 66 – reactivity feedback diagram

- simplified reactivity feedback diagram shows how feedback works to limit reactor reactivity changes
- positive reactivity change ($\boldsymbol{\rho_{EXT}}$) produces changes in reactor fuel temperature, moderator temperature, and moderator density that provide feedback in opposition to original reactivity change
- negative reactivity feedback, $\boldsymbol{\rho_F}$, functions to oppose planned or inadvertent positive changes in core reactivity; provides

assurance of controllable rate of change for reactor power level increases

Slide 67 – steady-state power operation graphic

- for steady-state operation, k = 1 and no reactivity (positive or negative) being inserted into system (i.e., $\rho_{EXT} = 0$)
- since no significant changes occurring in reactor physical parameters (e.g., fuel temperature, moderator temperature, moderator density, etc.) during steady-state operation, no reactivity feedback (i.e., $\rho_F = 0$) and reactor period is infinite

Slide 69 – step change power increase graphic

- to increase reactor power level, control rods partially removed from PWR core and coolant flow increased through BWR core
- these changes produce positive step change in reactor core reactivity (ρ_{EXT}) that is much less than delayed neutron fraction
- this produces corresponding increase in neutron multiplication factor;
  — k increases to value greater than 1, but less than 1 + β
- system reactivity change produces changes in fuel temperature, moderator temperature, moderator density, etc. that tend to oppose original reactivity change
- feedback reactivity (ρ_F) is negative for positive step change in reactivity and produces corresponding decrease in k, which causes k to return to value of 1 at new power level

Slide 70 – time-dependent power behavior for various reactivity changes graphic

- graphic illustrates time-dependent change in reactor power for selected positive and negative reactivity changes
- vertical axis shows normalized reactor power; that is, initial power set equal to 1.0
- positive reactivity change results in relatively rapid power increase due to prompt neutron generation followed by asymptotic power increase controlled by delayed neutron generation time
  — for positive reactivity change of 0.1%, reactor period approximately 80 seconds – a power change rate easily controllable by reactor operators
  — for positive reactivity change of 0.65% (prompt critical condition) reactor period about 0.08 second – a power change rate not controllable by reactor operators
- similar behavior observed for power decreases resulting from negative reactivity changes

Slide 73 – typical ex-core neutron detector locations graphic

- graphic shows typical reactor ex-core neutron detector locations
- three different types of neutron detectors

    - source range detectors used during reactor startup and shutdown
    - intermediate range detectors used during reactor's rise to full power
    - power range detectors used when reactor operating at full power
  - some overlap in neutron detector ranges

Slide 75 – typical PWR in-core neutron detector locations graphic

- graphic shows typical Westinghouse PWR in-core neutron detector locations
- flux thimbles are pressure tubes into which in-core neutron detectors inserted
- in-core neutron flux monitoring system typically consists of 4-6 movable miniature fission chambers depending on number of reactor coolant loops

Slide 76 – typical BWR in-core neutron detector locations graphic

- graphic shows possible locations for various BWR in-core neutron detectors as well as startup neutron source locations
- typically, 4 source range monitoring and 8 intermediate range monitoring detectors
- around 150 local power range monitoring detectors distributed throughout reactor core

Slide 77 – reactor control system

- xenon-135 and samarium-149 are by-products of U-235 fission and both isotopes have large thermal neutron capture cross-sections
    - Xe-135 radioactive with 9.1-hour half-life
    - Sm-149 is stable isotope
- both neutron absorbing isotopes present negative reactivity changes (i.e., they absorb neutrons) as they build up to steady-state levels in nuclear fuel during reactor operation
- following reactor shutdown Sm-149 continues to build up in reactor fuel due to radioactive decay of fission product promethium-149
    - during restart of previously operating reactor, Sm-149 presents positive reactivity changes as some of it "burned up" by neutron absorption before re-establishing its steady-state level during power operation

Slide 78 – reactor control system illustration graphic

- graphic shows simplified nuclear reactor control system
- reactor operator control capabilities based on information provided by plant monitoring instrumentation via operator information loop

- for circumstances where operator manual actions may be inadequate, appropriate actions automatically initiated via automatic information and control loop

Slide 81 – reactor startup simulation

- simulation for PWR core
- 48% insertion of control rods into reactor core results in reactor criticality (k = 1)
  - startup neutron source needed to initiate neutron multiplication, but not needed to sustain stable neutron population
- control rod insertion > 48% results in subcritical reactor (k < 1)
  - startup neutron source required to sustain stable neutron population

Slide 82 – subcritical reactor stable neutron population illustration for k = 0.5

- slide illustrates how stable neutron population achieved with neutron source in subcritical reactor core where neutron multiplication factor, k, is 0.5
  - 0.5 multiplication factor means one-half of system neutrons lost in each neutron generation
  - for neutron source adding 100 neutrons per generation, stable neutron population of 197 neutrons achieved in 7 generations
  - number of neutrons in each generation can be increased by incrementally removing control rods from reactor core to make more nuclear fuel available for fission events
  - increased fission rate increases value of k, which results in increased stable neutron population
- as long as reactor subcritical (k < 1), neutron source necessary to maintain stable neutron population
- once criticality achieved (k = 1), neutron population will remain stable without neutron source, which can be removed from reactor core
- Point of reference: to continuously generate 3000 megawatts of thermal energy in U-235 fuel requires stable neutron population of $\approx 10^{16}$ neutrons

Slide 86 – 1/M plot vs control rod withdrawal graphic

- graphic shows typical 1/M plot that allows extrapolation of plotted data to determine control rod bank withdrawal distance that will result in reactor criticality (k = 1)